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ISHTAR DEFORMED BELTS: EVIDENCE FOR DEFORMATION FROM BELOW?;
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The mountain belts of Ishtar Terra are unique on Venus. Models for their formation include mantle upwelling [1-2], mantle downwelling [3-4], and horizontal convergence [5-6]. The present forms of these models are too simple to predict surface strain, topography, or gravity. More detailed models will require specific constraints as imposed by geologic relations. In order to develop specific constraints for geodynamic models we examine the geology of Ishtar Terra as viewed in Magellan SAR imagery in an attempt to interpret regional surface strain patterns. In this paper we present geologic and structural relations that leads us to postulate that Ishtar deformed belts result from shear forces within the mantle acting on the lithosphere, and not by horizontal forces from colliding plates. We propose that the surface strains result from differential strain and displacement of domains within the upper mantle, and that further analysis of Ishtar deformation may allow us to identify individual domains within the mantle, and to constrain displacement trajectories between domains.

Introduction. Ishtar mountain belts, which surround Lakshmi Planum (4 km above mean planetary radius, MPR), are defined on the basis of deformation and topography (3.5-10 km MPR). Ishtar tessera terrains, which are also deformed, sit at lower elevations (1-4.5 km MPR) and lie outboard of the mountain belts. Fortuna tessera lies east of Maxwell Montes, Clotho tessera south of Danu, Atropos tessera west of Akna, and Iztpapalolt tessera lies north of western Freyja Montes. In the case of Maxwell and western Fortuna, Danu and Clotho, and Akna and eastern Atropos, the dominate structural trend of the mountain belt is mimicked by parallel structures in the adjacent tessera. In these cases the major difference between the mountain belt and neighboring tessera is topographic relief. Ridges, interpreted as contractional features [7-10], define each mountain belt and adjacent tessera. Extensional structures are preserved locally and indicate that gravity spreading accompanied crustal shortening [11].

Observations. In addition to high elevations, models for Ishtar deformed belts must explain numerous geologic and structural relations derived from Venera and Magellan imagery. 1. Lakshmi Planum is relatively free of deformation. 2. Each deformed belt is defined by a characteristic structural fabric that is developed across the width of the deformed belt; temporal relations across each belt are difficult to discern. 3. This structural fabric ends abruptly along strike without evidence of truncating faults; the termination typically corresponds with a change in slope (e.g. southern and northern Maxwell Montes). 4. The structural fabric is dominantly contractional in origin [7-14]. Limits of crustal strain can be estimated assuming ridges are continuous folds. Wavelengths of 6-10 km with amplitudes of 1, and 2 km (almost certainly a gross exaggeration), yield 2-5%, and 8-20% shortening, respectively. 5. Within Akna, and locally in Freyja and Maxwell, extensional fractures trend normal to the fold axes which define the ridges [e.g., 14]. Folds and fractures formed synchronously, and are consistent with shortening perpendicular to the ridge trends. This character of deformation is rheologically akin to that of viscous lava [14]. 6. Volcanism is present in most of the deformed belts, and occurred late in the deformation history. Lava fills structural valleys, yet local small-scale ridges that deform the valley fill parallel adjacent fold ridges, and are therefore indicative of local late-stage shortening that continued after flooding [10-11]. 7. Lava filled valleys cover 100's of thousands of square km (e.g. Akna and Atropos), yet few, if any, obvious vents or channels are identified. 8. In plan view the mountain belts and their tessera are short and squat, they each have length (measured parallel to the trend of dominant structural fabric) to width (measured normal to the trend of structural fabric) ratios < 2, with the exception of Danu Montes with length:width of 15 (Clotho tessera has length:width of 1.9) and Iztpapalotl tessera with length:width of 5. In comparison, terrestrial mountain belts typically have length:width values > 7, and values > 10 are common (e.g. the Appalachian and Andean belts). Terrestrial belts mark present or ancient plate boundaries.

Model. In modeling Ishtar deformation we follow premises outlined by Solomon et al. [13], the most pertinent of which are: 1. The elastic lithosphere is only a few tens of km thick due to high surface temperature [15]. 2. A 10-30 km thick crust has two elastic lithospheres, one in the upper crust, and one in the upper mantle [16-19]. 3. The weak lower crust can detach along a ductile decollement [20]. 4. Viscous mantle flow can induce horizontal stresses in the lithosphere and cause intense tectonic deformation [21]. 5. Lithosphere is limited in its ability to move horizontally due to a lack of a low-viscosity zone [21].

The very small aspect ratios of Ishtar deformed belts (they are, in fact, not true belts, but rather deformed domains) distinguishes them from their terrestrial counterparts, and holds a key to their formation. This, taken together with the relatively uniform distribution of strain over extremely large areas (300 to 1,000 km normal to structural trend), the lack of obvious temporal development of the structures, and modest values of shortening (2-20%) which can be accommodated by the structural fabric, argues for deformation from below, rather than horizontally across the deformed domains. If, as in the case of terrestrial mountain belts, deformation resulted from horizontal transmission of stress, the development of structures normal to strike should be time transgressive, should exhibit differences in structural styles, such as foreland and hinterland deformation, and would not be distributed over a region 1,000 km normal to the structural trend. Therefore, the distribution of relatively uniform deformation that records modest strain over large regions with small aspect ratios suggests Ishtar deformation results from forces transmitted from below the crust, rather than from forces transmitted horizontally as in plane forces.

Furthermore, the observation that characteristic structural fabrics continues, in a direction normal to structural trend, from mountain belt to adjacent tessera, across changes in elevation of 2-6 km, indicates that these structures are not specifically related to topography. Similarly, the abrupt termination of structural fabric along strike with no obvious truncating faults, and the coincidence of this termination with topographic slopes suggests that mountain belt topography is defined by something other than the structural fabric. In addition, the modest shortening which can be accommodated by the ridges of Ishtar mountain belts and tessera terrains (<25%) is not sufficient to support the elevated topography of these regions. Each of these observations argues, therefore, that the structures themselves are not responsible for the elevation of the deformed belt. The simplest explanation then, is that the topography of the deformed belts results from below.

On a related point, the regionally distributed (passive) volcanism seems paradoxical to the high topography of the deformed belts if the deformed belts result from thickened crust [10-11].

We propose a model for Ishtar deformation in which the surface strain results from stresses below the crust rather than from horizontal forces of colliding plates. Basilevsky et al. [22] suggested that sub-lithospheric flow might be responsible for large regions of deformation given the lack of plate tectonic features interpretable from Venera images. Phillips [21,23] modeled viscous flow in the interior of Venus and illustrated flow can induce horizontal stresses capable of intense lithospheric deformation. Our model follows this original suggestion.

In the model, domains within the upper elastic mantle transmit stresses to the overlying crust, which deform in tablecloth fashion. The observations require that the crust be partly decoupled from the mantle such that it can deform, yet coupled to the elastic mantle such that shear strain acting on the elastic mantle (presumably in response to mantle convection) can be transmitted to the upper crust. The two layer crust deforms in parasitic structures over the elastic mantle; the upper, strong crust deforms in folds with local extensional fractures. The lower crust deforms in a ductile fashion, and provides a source of partial melt, which given the appropriate tectonic conditions (pressure release melting) could be leaked to the surface. Each structural and topographic domain within Ishtar Terra could be underlain by a discreet domain, or by transitions between domains, within the upper mantle. Differences in viscosity, thickness, and displacements define individual domains. For example, Lakshmi Planum may be underlain by a strong, immobile mantle, and the uncharacteristically large aspect ratio of Danu and Itzpapalotl might indicate their locations above domain boundaries. Danu would lie above a transition between Lakshmi upper mantle, and that of Clotho tessera. Itzpapalotl may lie above a broad transitional domain between plains mantle and strained mantle of Freyja Montes, and its apparent structural asymmetry [24] may record northeast translation of the plains block relative to the mantle domain which underlies Freyja.

In this model the evolution of Ishtar deformed belts is very different from that of terrestrial mountain belts, which result from horizontal forces of colliding plates. The closest terrestrial analog is that of the Tertiary Laramide orogeny that affected western North America from Montana to Texas, and Nevada to Colorado. Laramide deformation was due to extremely low angle subduction of the Farallon plate beneath North America, and resulted from stresses transmitted from below across the horizontal plate boundary [25-26].

In summary, we propose that Ishtar deformation results from stresses below the crust rather than from horizontal forces of colliding plates. Individual deformed belts within Ishtar Terra might be underlain by discreet domains within the upper mantle. Domains could be defined by changes in viscosity, thickness, and displacement rates and trajectories. Detailed structural and kinematic mapping of Ishtar deformation may allow us to identify individual domains, and to constrain spatial and temporal displacement trajectories between domains. Such results would place important constraints on geodynamic models.

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